THE INSTALLATION AND APPLICATION OF SENSORS FOR TURBOMACHINERY MONITORING

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ABSTRACT

Turbomachinery performance quantities commonly monitored are bearing temperatures, thrust bearing load, and rotor vibration, speed, and axial position. Various sensors utilized in the monitoring function and installation configurations are presented. Factors contributing to sensing errors are identified.

I. INTRODUCTION

Various turbomachinery operating functions are monitored as indicators of machine performance. The functions commonly monitored include bearing temperature, bearing load, rotor speed, rotor axial position, and rotor vibration. While there is general agreement in selecting the functions to be monitored, there is also a need for uniformity of the instrumentation sensing of these functions.

Variations of instrument sensing is reflected in the acquired data. Similar performance is indicated differently by the monitors using different sensing. Consequently, the criteria for acceptable performance as indicated by the monitor is a function of the sensing. Also comparison of machine performance is restricted because of the lack of a uniform data base.

In 1970 an electrical instrumentation standardization program was initiated by the Elliott Company, Jeannette, Pa., for the purpose of establishing and implementing instrumentation standards in turbomachinery. The following reflects the current status of this program.

II. SENSORS

Certain sensors are widely used and are generally accepted. They have demonstrated compatability with existing instrumentation, they have been successfully incorporated into the machine design, and the user is familiar with the acquired data and performance readout. The following is a list of the commonly used sensors:

FUNCTION	SENSOR
Bearing Temperature	Imbedded Thermocouple Imbedded RTD
Bearing Load	Load cell imbedded in self-equalizing thrust bearing
Speed	Magnetic pick-up with tooth gear
	Eddy current proximity system with shaft discontinuity
Rotor Axial Position	Eddy current proximity system
Rotor Vibration	Eddy current proximity system
Rotor Radial Position Reference	Eddy current proximity system with shaft discontinuity

The rotor radial position reference is added for completeness. While not a monitored function, the reference is required for data reduction of the rotor vibration data.

Acceptable methods have been developed to utilize commercially available configurations of the load cell, the magnetic pick-up, and the eddy current proximity probe. Because both RTD's and thermocouples are widely used, a common configuration was developed. This is shown in Figure 1. The salient features are the "top hat" configuration and the stranded lead wire.

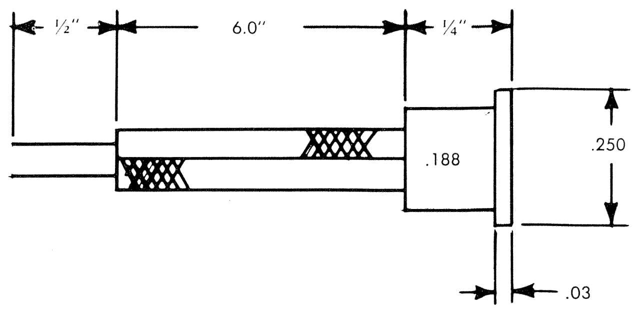


Figure 1. Imbedded Bearing Temperature Sensor Configuration.

The "top hat" configuration serves two purposes. The position of the sensor with respect to the bearing surface is controlled for consistency by drilling the shoulder. The "top hat" brim resting on the shoulder in the bearing provides structural support for the babbitt surface. This prevents movement of the sensor that would allow a depression to be created at the bearing surface.

During early development solid lead wire was used and frequent lead wire breakage was experienced. To correct this, stranded lead wire is now used for both RTD's and thermocouples.

III. SENSOR INSTALLATION

In developing the sensor installations, basic consideration was given to ease of maintenance. The proximity probe assembly was designed to enable probe replacement and calibration without special equipment and without removing the machine from service. However, similar capability could not be developed for the bearing sensors. Therefore, the design features ruggedness to prevent failure.

The installation of the temperature sensor into a liner journal bearing, a tilt pad journal bearing, and a tilt pad thrust bearing is shown in Figure 2a, 2b, and 2c respectively. First, a .196″ hole is drilled through the bearing and then a .260″ counterbore .060″ deep. With the sensor brim resting on the counterbore, the top of the sensor is 0.030″ below the bearing surface. Babbitt is then puddled onto the sensor and scraped smooth. Where space permits, a terminal strip is installed as shown in Figure 2b and 2c to facilitate replacement of the lead wire. A braided sheath protects the lead wire from abrasion and dampens vibration of the wire. Soldering the sheath to the bearing provides strain relief. The resulting assembly is quite rugged and is capable of withstanding considerable abuse.

The load cell for sensing bearing load is installed under an equalizing block of a self-equalizing thrust bearing. Figure 3 shows the load cell and Figure 4 shows the installation in the bearing. Clearance for the sensor is obtained by reducing the height of the equalizing block. The sensor is then installed between the equalizing block and base ring.

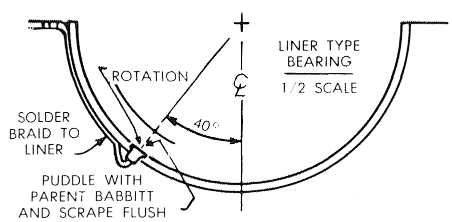


Figure 2a. Temperature Sensor Imbedded in Liner Journal Bearing.

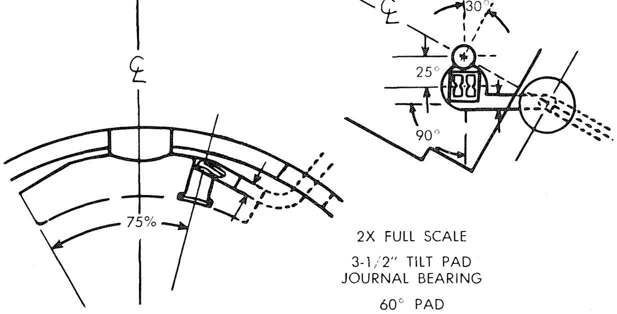


Figure 2b. Temperature Sensor Imbedded in Tilt Pad Journal Bearing.

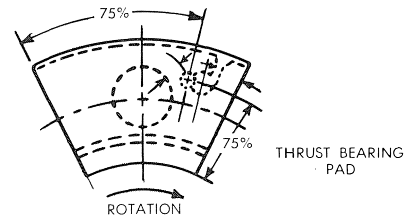


Figure 2c. Temperature Sensor Imbedded in Tilt Pad Thrust Bearing.

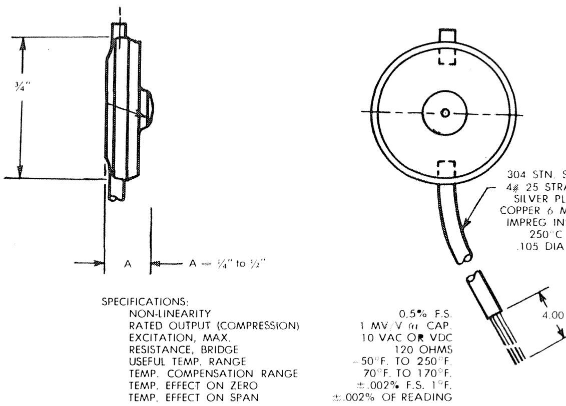


Figure 3. Load Cell Bearing Load Sensing.

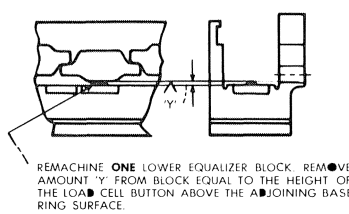


Figure 4. Load Cell Installation in Self-Equalizing Thrust Bearing.

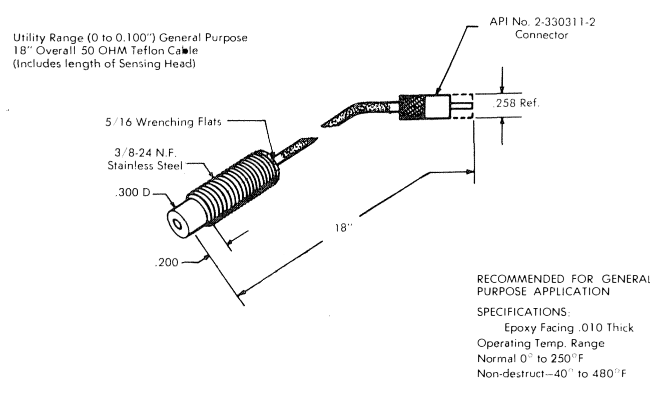


Figure 5. Eddy Current Proximity System Sensing Probe.

The eddy current proximity system is used for all rotor functions; speed, vibration, axial position, and radial position reference. The eddy current proximity system is comprised of a probe, interconnective cable, and an oscillator detector. These are shown in Figures 5, 6, and 7 respectively.

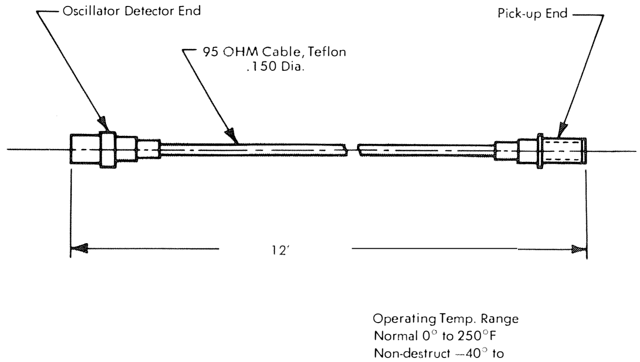
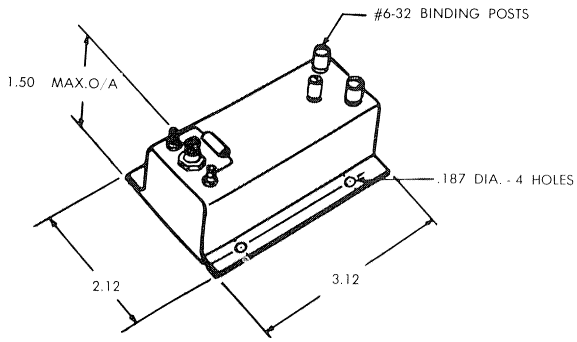


Figure 6. Eddy Current Proximity System Interconnecting Cable.



SPECIFICATIONS:

Co-axial cable length 12' only (95 OHM)
Output polarity - Negative with respect to common.
Operating Temperature Range
Normal: −20° To +200°F (−29° To +93°C)
Non-destruct - 40° To 250°F
Sealed or encapsulated to prevent dirt and moisture from harming components.
Units must be interchangeable without the need for recalibration of the system.

Figure 7. Eddy Current Proximity System Oscillator-Detector.

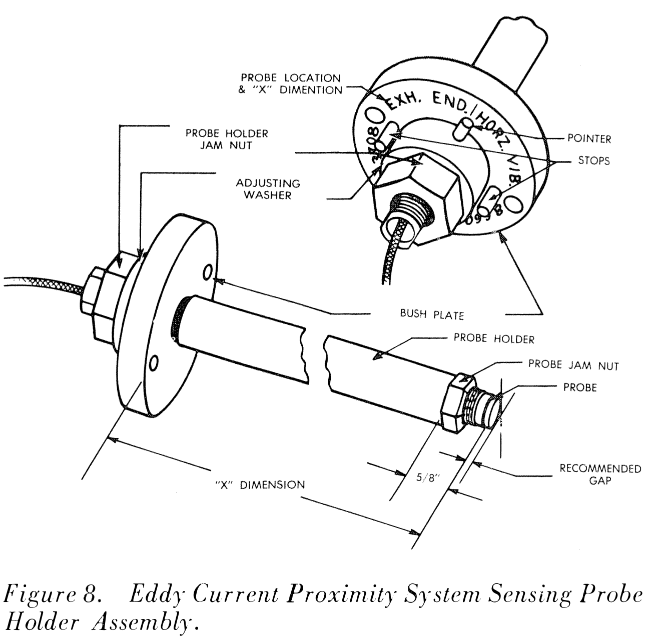


Figure 8. Eddy Current Proximity System Sensing Probe Holder Assembly.

The eddy current probe is mounted in an assembly that satisfies external removable and adjustable requirements. This assembly is shown in Figure 8.

The salient features of this assembly are the ability to replace the sensor probe and reinstall the properly gapped assembly in the machine without using the sensor for alignment. The key to this is in establishing "X" dimension during assembly and recording this dimension on the assembly itself. The cam stops limit adjustment of the adjusting washer to $\pm 1/4$ turn from the zero position resulting in an adjustment range of 0.222″ or $\pm 0.011''$. It is this feature that enables self calibration. By rotating the adjusting washer between the zero position and the pin stops and reading the oscillator detector output voltage at each point, a three point calibration check of the scale factor to better than 5% is obtained.

IV. SENSING ACCURACY

The objective of the instrumentation sensors is the conversion of the desired function into a usable signal for the instrumentation. The usefulness of these signals is a function of the accuracy with which the signal is representative of the desired function. The following are the significant sensing errors for the various functions.

Bearing temperature errors are introduced by the lead wire between the RTD sensor and the instrumentation. For example, the resistance of #26 AWG is 40.81 Ω/k ft. and the temperature coefficient of copper wire is 0.00393 Ω /°C. Using the nickel element RTD for reference this translates into an offset error of 0.05°C/ft. of lead wire and a temperature coefficient uncertainty of 0.002°C/ft. of lead wire. This is relatively insignificant for short distances. One sensor manufacturer indicates a maximum distance of 4 ft. in its specifications. Lead wire error can be compensated by using a three lead wire system. As shown in Figure 9, this places equal lead wire resistance in two legs of the bridge network in the instrumentation, eliminating the effect of lead wire.

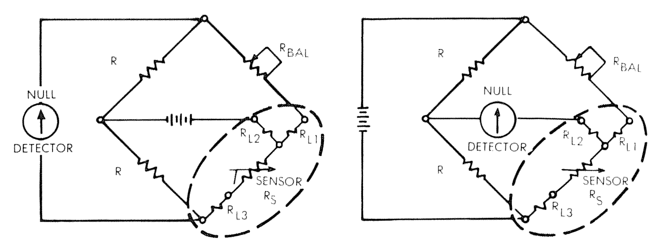


Figure 9. Diagram Showing Three Wire Compensation for RTD Lead Wire.

Another source of error is the temperature drop between the bearing surface and the sensor. The bearing surface is exposed to high temperature oil. The rear surface of the bearing is exposed to low temperature oil. If the temperature gradient across the bearing is uniform then the temperature at the sensing element is reduced by the ratio of dimensions. For 130° F across a 1/4″ bearing the temperature at the sensor would be 16° F below the surface temperature. More rigorous analysis is required to determine the magnitude of error more accurately; however, the relative magnitude of error overwhelms the other sensor errors presented.

Rotor speed sensing detects events per turn. The quantization error or resolution is a function of the number of events per turn and the sampling time interval. The relationship is as follows:

$$\text{Resolution} = \frac{60}{\text{Events per turn x sample time (sec.)}} \text{ RPM}$$

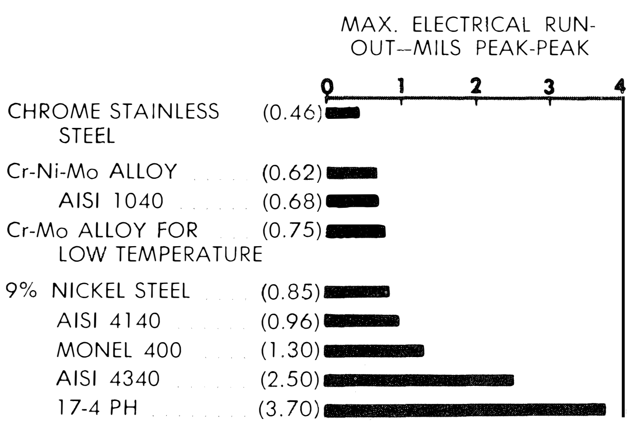
This expression shows that the greater the events per turn and the longer the sample time the smaller the resolution. Physical constraints limit the events per turn. Large sample time intervals would introduce time lag errors when the rotor is accelerating. Typical values are 60 events/turn and a sample time of 1 sec. At maximum constant acceleration of a 20% rated speed change per second machine, the speed error would be a minimum of 10% of operating speed.

The eddy current proximity system assembled from individual components as received has an accuracy of ±10%. With full scale readout of 1, 3, and 10 mil, the system accuracy is ±0.1, ±0.3, and ±1.0 mil respectively. With calibration the system accuracy can be improved to ±2%.

Additional errors are mechanical and electrical runout. Mechanical runout is shaft eccentricity and the manufacturing tolerance is ±0.2 mil. Electrical runout is a false indication of relative displacement due to shaft anomalies that is indistinguishable from actual displacement.

A test program was conducted at the Carrier Research Division, Syracuse, N.Y. to study electrical runout. Nine samples of the various shaft materials were used for this study. The basic electrical runout for these samples ranged between 0.4 and 3.7 mil. Table 1 shows the magnitude of runout for the individual samples.

Table 1. Apparent electrical runout indicated by eddy current probe measurement for various shaft materials.



The shaft samples were manufactured with a 16 finish and an eccentricity of 0.0002″. The sample was slowly rotated and the mechanical runout was confirmed negligible by measurement. The eddy current proximity system was calibrated for each sample. Readout was measured at the oscillator detector output eliminating readout instrumentation suppression and scale factor error.

The effects of cold bathing, surface acid etching, and magnetization/degaussing were investigated. Cold bathing and acid etching had no significant effect on electrical runout. When magnetized, the runout pattern was altered with an overall increase in the magnitude of electrical runout. When subsequently degaussed the original runout pattern and magnitude were restored.

Routine measurement of electrical runout on all shafts has been implemented. The shaft is mounted on "V" blocks and rotated by hand. Strip chart recordings of the oscillator detector output are made for permanent record and at the same time mechanical runout is measured and recorded. To date 46 shafts have been measured. Of the 46, nine had excessive electrical runout and were degaussed. The electrical runout of six of those shafts was significantly reduced, but the electrical runout of 3 shafts was not significantly reduced by degaussing.

When applied to axial position sensing the basic eddy current proximity system has an off-the-shelf tolerance of ±10%. With calibration the system accuracy can be improved to ±2%. Mechanical and electrical runout are averaged and do not contribute additional error. However, the temperature effects in the form of bias shift are indicated as displacement.

Test data indicate that the accuracy of the bearing load detector is ±10% which is considerably greater than the sensor tolerance. The accuracy of the readout is affected by placing shims under the detector. This indicates that the self-equalizing pads may not completely equalize the bearing load because of dimensional tolerances.

V. SUMMARY

Uniformity of instrumentation sensing offers many advantages. A common base of reference for the acquired data would enable industrywide comparison of machine performance. Consistent acceptable performance criteria could be established. Communications between user and manufacturer could be simplified and more effective because of the common base of reference. Special engineering design to incorporate the sensors into the machine would be reduced. In general, standardization of instrumentation sensing would improve the effectiveness of machine performance monitoring and reduce manufacturing cost.

ACKNOWLEDGEMENTS

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REFERENCE

Schanzenbach, G.P., "Reduction of Electrical Runout to Improve the Accuracy of Eddy Current Probe Sensing of Turbomachinery Vibration", Carrier Corporation Research Division, Syracuse, N.Y., ASME 72-Lub-R.